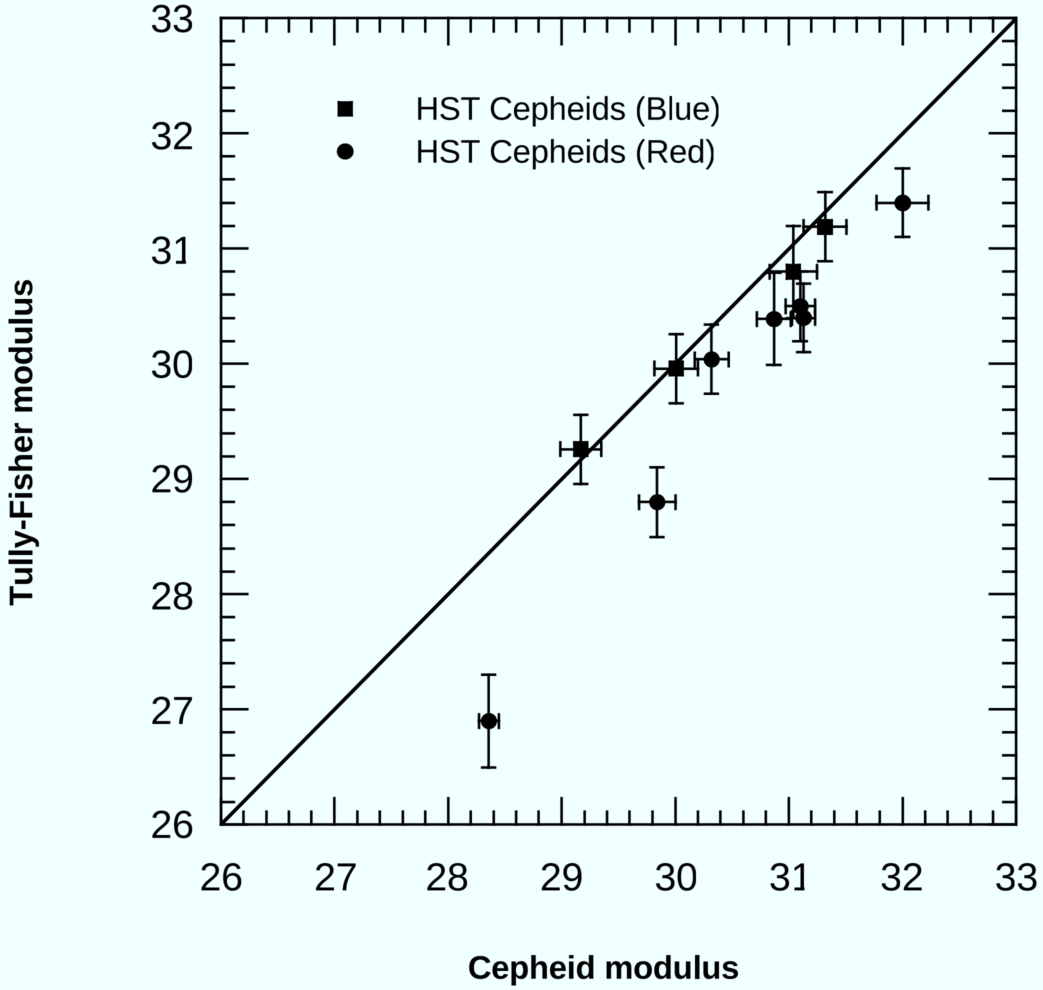

HST Cepheids (Blue)
HST Cepheids (Red)
Tully-Fisher modulus
Cepheid modulus
26
27
28
29
30
31
32
33

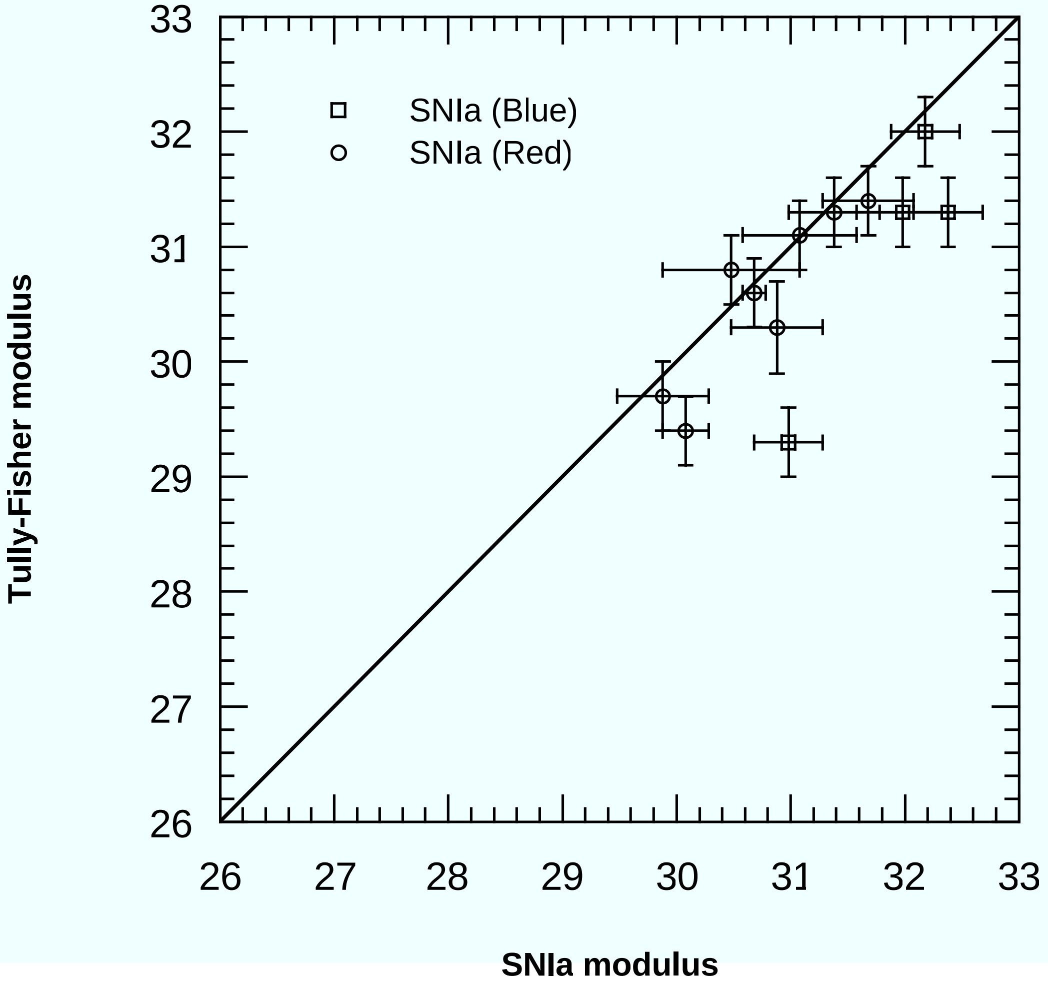

SNIa (Blue)
SNIa (Red)
Tully-Fisher modulus
SNIa modulus
26
27
28
29
30
31
32
33

Table 1. Distance Moduli, Tully -Fisher Parameters and Colours for Galaxies with HST Cepheid Distances.

Galaxy Name (1)	Cepheid $(m-M)_o$ (2)	TF $(m-M)_o$ (3)	Ceph.-TF $(m-M)_o$ Residual (4)	Inc. (deg) (5)	log W^i_R (6)	B_T-I_T (7)	A^i_B (8)	A^b_B (9)	B-I corr (10)	Comments (11)
IC4182	28.36±0.09[1]	26.90±0.4	1.46	30	1.937	0.87	0.04	0.00	0.85	
NGC4536	31.10±0.13[2]	30.50±0.3	0.60	70	2.525	1.90	0.38	0.00	1.69	Virgo
NGC4639	32.00±0.23[3]	31.40±0.3	0.60	55	2.510	1.78	0.17	0.05	1.66	Virgo
NGC4496A	31.13±0.10[4]	30.40±0.3	0.73	43	2.328	1.52	0.09	0.00	1.47	Virgo
NGC0925	29.84±0.16[5]	28.80±0.3	1.04	57	2.349	1.58	0.19	0.24	1.34	
NGC3351	30.01±0.19[6]	29.96±0.3[10]	0.05	47[10]	2.511[11]		0.11[11]	0.05[11]	1.45[11]	Leo (M95)
NGC3621	29.17±0.18[6]	29.26±0.3[11]	-0.09	54[11]	2.471[11]	1.45[11]	0.17[11]	0.42[11]	1.12[11]	
NGC4321	31.04±0.21[7]	30.80±0.4	0.24	28	2.700	1.76	0.05	0.00	1.73	Virgo(M100)
NGC1365	31.32±0.19[6]	31.19±0.3[12]	0.13	44[12]	2.760[12]	2.01[11,12]	0.09[11]	0.00[11]	1.96[11]	Fornax
NGC4571	30.87±0.15[8]	30.39±0.4[13]	0.48	35[13]	2.427[13]	1.95[13]	0.00[13]	0.11[13]	1.89[13]	Virgo
NGC3368	30.32±0.15[9]	30.04±0.3[10]	0.28	46[11]	2.641[11]		0.10[11]	0.06[11]	2.08[11]	Leo (M96)

Notes.

1. Where no reference in Columns (3), (5), (6), (7), (8), (9), (10) is given the data is taken from Pierce (1994). Other references are: 1. Saha et al 1994, 2. Saha et al 1996a, 3. Sandage et al 1996, 4. Saha et al 1996b, 5. Silbermann et al 1996, 6. Freedman 1997 and refs therein, 7. Freedman et al 1994, 8. Pierce et al 1992, 9. Tanvir et al 1995, 10. Pierce (priv. comm.) reported by Ciardullo et al 1989, 11. This paper with parameters taken from The Third Reference Catalogue, following precepts of Tully & Fouque 1985, 12. Bureau, Mould & Staveley-Smith 1996 13. Pierce & Tully 1988.

2. In Column (2), the NGC4571 Cepheid distance modulus comes from ground-based rather than HST observations.

3. In Column (3) the TF distance for NGC3621 is based on an I_T derived from de Vaucouleurs & Longo (1988) using $(V-I)_{Johnson}=1.3(V-I)_{KC}$ to convert $I_{Johnson}$ into I_{KC} and an aperture correction of 0.35 mag, giving I_T=8.83mag.

4. Column (4) contains the Cepheid-TF distance modulus residual, Column (5) contains the galaxy inclination, Column (6) contains the corrected 21cm line-width, Columns (7) contains the galaxy colour, Columns (8) and (9) contain the B band absorption corrections for galaxy inclination and Galactic latitude, Column (10) contains the absorption corrected galaxy colour assuming $A_I=0.44A_B$, Column (10) contains details of galaxy cluster or group membership and galaxy Messier numbers.

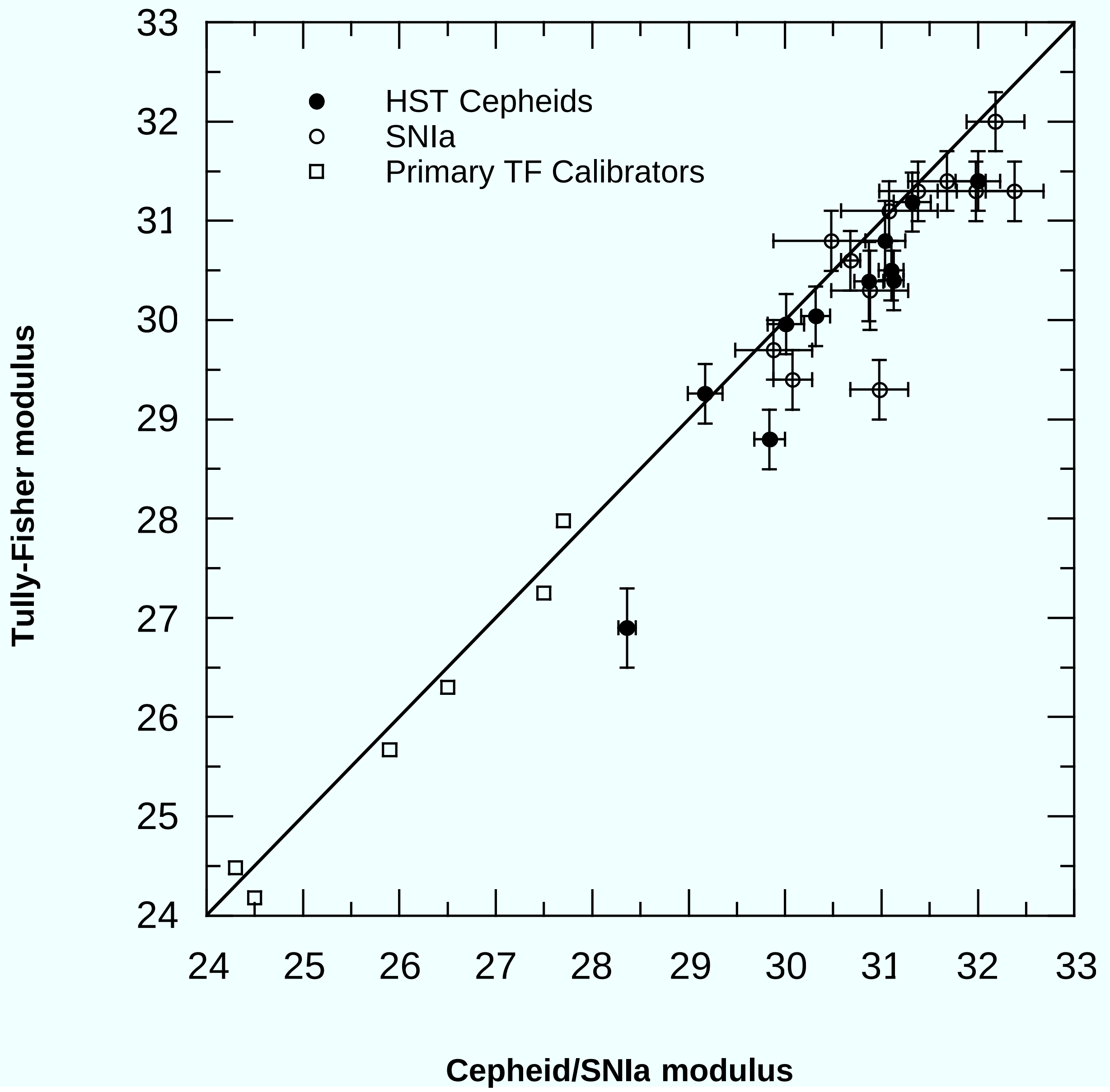

HST Cepheids
SNIa
Primary TF Calibrators
Tully-Fisher modulus
Cepheid/SNIa modulus
24
25
26
27
28
29
30
31
32
33

Table 2. Tully-Fisher Parameters and Colours for SNIa Galaxies.

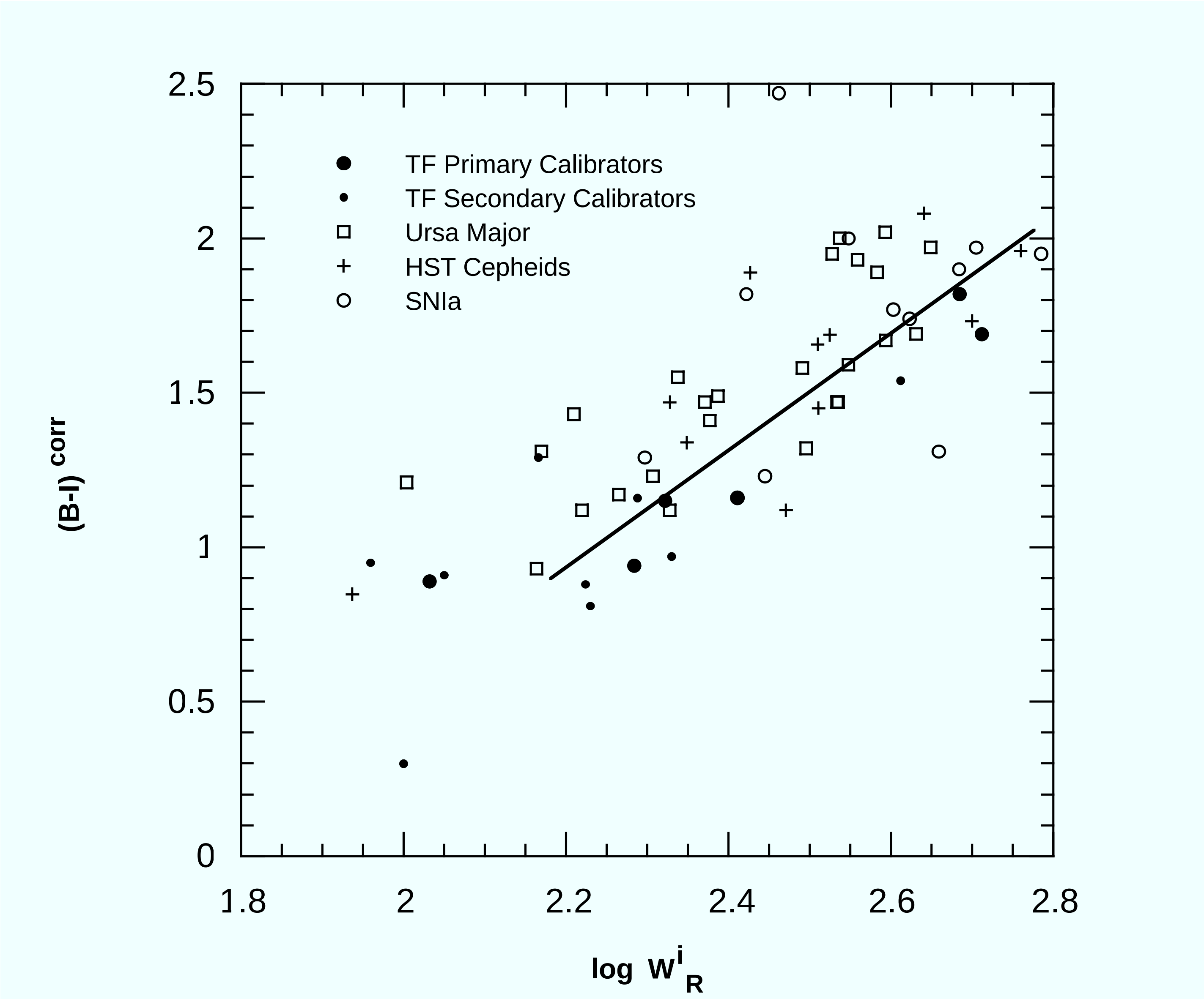
Galaxy (1)	SNIa (2)	SNIa $(m-M)_o$ (-19.38) (3)	A_B (SNIa) (4)	TF $(m-M)_o$ (5)	SNIa-TF $(m-M)_o$ Residual (6)	log W^i_R (7)	(B-I) corr (8)
NGC1003	1937D	29.88±0.4	2.2	29.7±0.3	0.18	2.297	1.29
NGC3992	1956A	31.68±0.4	0.3	31.4±0.3	0.28	2.684	1.90
NGC2841	1957A	31.98±0.4	1.8	31.3±0.3	0.68	2.785	1.95
NGC3389	1967C	32.38±0.3	0.4	31.3±0.3	1.08	2.445	1.23
NGC5055	1971I	30.98±0.3	0.5	29.3±0.3	1.68	2.623	1.74
NGC6384	1971L	32.18±0.3	0.0	32.0±0.3	0.18	2.659	1.31
NGC4414	1974G	31.38±0.4	0.5	31.3±0.3	0.08	2.696	
NGC4402	1976B	30.48±0.6	4.3	30.8±0.3	-0.32	2.422	1.82
NGC4419	1984A	30.88±0.4	0.8	30.3±0.4	0.58	2.462	2.47
NGC3627	1989B	30.08±0.2	1.8	29.4±0.3	0.68	2.603	1.77
NGC4579	1989M	31.08±0.5	1.0	31.1±0.3	-0.02	2.705	1.97
NGC4527	1919T	30.68±0.1	0.3	30.6±0.3	0.08	2.548	2.00

Notes.

1. In Column (3), the supernova distance uses the B^o_{max} listed by Pierce (1994), calibrated using the average of five SNIa with Cepheid distances from Saha et al (1994, 1995,1996a,b and Sandage et al (1996) as described in the text.

2. The SNIa Bband absorption in Column (4), the Tully-Fisher distance modulus in Column (5), the corrected TF line-width in Column (7) and the corrected B-I colour in Column (8) are taken from Pierce (1994).

3. Column (6) contains the Cepheid-TF distance modulus residual.



TF Primary Calibrators
TF Secondary Calibrators
Ursa Major
HST Cepheids
SNIa
(B-I) corr
log W i R
2.5
2
1.5
1
0.5
0
1.8
2
2.2
2.4
2.6
2.8

A Test of the Calibration of the Tully-Fisher Relation Using Cepheid and SNIa Distances.

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Summary. **We make a direct test of Tully-Fisher distance estimates to eleven spiral galaxies with HST Cepheid distances and to twelve spiral galaxies with Type Ia supernova (SNIa) distances. The HST Cepheid distances come from the work of Freedman (1997 and references therein), Sandage et al (1996 and references therein) and Tanvir et al (1995). The SNIa distances come from Pierce (1994), calibrated using the Cepheid results of Sandage et al (1996). The Tully-Fisher distances mostly come from the work of Pierce (1994). The results show that the Tully-Fisher distance moduli are too short with respect to the Cepheid distances by 0.46±0.14mag and too short with respect to the SNIa distances by 0.46±0.19mag. Combining the HST Cepheid and SNIa data suggests that, overall, previous Tully-Fisher distances were too short by 0.46±0.11mag, a result which is significant at the 4σ level. These data therefore indicate that previous Tully-Fisher distances should be revised upwards by ≈24±6% implying, for example, a Virgo distance of 19.3±1.9Mpc. The value of H_o from Tully-Fisher estimates is correspondingly revised downwards from H_o=84 ± 10kms^{-1}Mpc^{-1} to H_o=68 ± 8 kms^{-1}Mpc^{-1}.**

1. Introduction.

Over the past twenty years, the Tully-Fisher (TF) relation has been one of the main pieces of evidence suggesting that Hubble's constant, H_o, was high, in the region $H_o \approx 85 kms^{-1} Mpc^{-1}$, (eg Tully & Fisher 1977, Aaronson et al 1986, Pierce & Tully 1992). The power of the Tully-Fisher route to H_o was that it was able to be calibrated in the Local Group and its immediate neighbourhood, since six nearby spirals, including M31 and M33, had both Tully-Fisher and ground-based Cepheid distance estimates. This meant that only a single step was needed to proceed from the Local Group to more distant galaxy clusters such as Virgo, Fornax and Centaurus. There had been concerns voiced about both the accuracy and reliability of the Tully-Fisher relation (eg Bottinelli et al, 1986, Sandage, 1988, Kraan-Korteweg, Cameron and Tammann, 1988). However, with a lack of primary distance indicators, such as Cepheids, in more distant galaxies these claims were difficult to check.

Here, we use eleven newly available Cepheid distances from the HST Distance Scale Key project (Silbermann et al 1996, Freedman, 1997 and references therein) and from other HST (Saha et al 1994, Tanvir et al 1995, Saha et al 1996a,b, Sandage et al 1996) and ground-based (Pierce et al, 1992) observations to test the previous TF calibration. We shall supplement the Cepheid-TF data with twelve SNIa-TF galaxies, ie galaxies which have both SNIa distances and TF distances. Since the SNIa scale now has five, Cepheid calibrated, SNIa luminosities (Sandage et al, 1996 and refs. therein), this provides a further way to test the calibration of the TF scale. This dataset is now large enough that we can restrict our attention to considering only those galaxies with both Cepheid/SNIa and TF distances. In particular, at no point do we make any assumption about the possible association of the Cepheid/SNIa galaxies with either galaxy groups or clusters (c.f. Tanvir et al 1995, Silbermann et al 1996, Sandage et al 1996).

2. Observational Data.

Table 1 lists the eleven galaxies with both Cepheid distances and TF distances. In all cases the Cepheid distances are from HST except for NGC4571 where the Cepheid distance comes from recent ground-based data (Pierce et al, 1992). The source of the Cepheid absolute distance moduli for all eleven galaxies is given and the listed results are the same as the values reviewed by Freedman (1997) in the ten overlapping cases quoted. The source of the TF parameters and the B-I colours are also given. In nine cases, the TF distance moduli come from the work of Pierce (1994) or Pierce & Tully (1988) or, in the cases of NGC3351 and NGC3368, from a Pierce & Tully private communication, quoted by Ciardullo et al (1989). In the case of NGC1365, the TF distance modulus, I_T magnitude and the linewidth comes from Bureau et al (1996) who use the precepts of Tully and Fouqué (1985), consistent with the procedures of Pierce (1994). In the case of NGC3621, we have taken the linewidth from the Third Reference Catalogue (de Vaucouleurs et al, 1991) and obtained the total Kron-Cousins magnitude, I_T, by converting the $I_{Johnson}$ aperture magnitude from de Vaucouleurs & Longo (1988). The TF distance is then found also following the procedures of Pierce (1994).

The B_T-I_T colours come in seven cases from the work of Pierce (1994) and Pierce & Tully (1988). In the cases of NGC3351 and NGC3368, where the Pierce & Tully CCD data is not yet published, we have taken the linewidths from the Third Reference Catalogue, and inferred the corrected I_T magnitudes from the Pierce & Tully TF distance moduli quoted by Ciardullo et al (1989). For these two galaxies and for NGC3621 and NGC1365, we then took B_T and the axial ratio R_{25} from the Third Reference Catalogue and produced corrected B_T-I_T colours and linewidths in a manner consistent with the procedures of Pierce (1994). Thus the results for the TF parameters and galaxy colours in Table 1 either come directly from the work of

Pierce(1994) or Pierce & Tully (1988) or have been determined using methods similar to theirs.

Only two galaxies with HST Cepheid distances have been excluded from our analyses. We have been unable to obtain a TF distance for NGC5253 because of the lack of a published I band magnitude. Also, M101 has been excluded because it is too face-on to apply the TF relation.

The six galaxies with previous ground-based Cepheid distances on which the Pierce & Tully (1992) TF calibration was based, M31, M33, NGC2403, M81, NGC300 and NGC3109, are also not included in the initial comparison in Section 3 because our first aim here is to make an *independent* test of the calibration that these galaxies produced. These galaxies appear later in the full comparison in Section 4.

Table 2 shows a further twelve galaxies which have both TF and SNIa distances. This sample was simply taken from Table 1 of Pierce (1994), excluding those galaxies which already appear in our Table 1 above, together with M31 and three galaxies which Pierce did not use, due to lack of supernova reddening information. To calibrate the SNIa luminosity, we simply take the absolute B magnitudes of four supernovae (SN 1937C, SN 1972E, SN 1981B, SN 1990N) with Cepheid distances from Saha et al (1994, 1995, 1996a, Sandage et al, 1996) as listed in Table 2 of Hamuy et al (1997). To these we added SN1960F taking the corrected, B magnitude at maximum, B^o(max), from Table 1 of Pierce (1994) and the distance from Saha et al (1996b). Taking the average of these five absolute B magnitude luminosities we obtain M_B(max)=-19.38±0.11 (excluding SN1960F because of uncertainty in its reddening would give M_B(max)=-19.40±0.14). This is between the value of M_B(max)=-19.47±0.07 quoted by Sandage et al (1996) and the value M_B(max)=-19.05±0.38 quoted by Hamuy et al (1997) when they do not correct for the proposed SNIa decay rate-peak luminosity correlation. Most of the galaxies in Table 2 do not

have accurate enough light decay rates to allow use of this correlation (D. Branch, priv. comm.). Our calibration is different from the value of Sandage et al because we omit SN1895B because of possible photometry problems and SN1989B where there is only a possible group association between the galaxy containing the Cepheids and the galaxy containing the supernova. Our calibration also differs from that of Hamuy et al (1997) because we only use SNIa galaxies with primary Cepheid distances and not those where only secondary distance indicators exist. Applying our calibration gives the SNIa distances in Table 2. The remainder of the table lists the TF and corrected B-I colour data for this sample, all of which are directly quoted from Pierce (1994).

3. Comparison of Cepheid/SNIa and Tully-Fisher Distances.

Figure 1a shows the plot of Cepheid versus TF distance for the eleven galaxies in Table 1. It can immediately be seen that there is a systematic offset between the two in the sense that all the TF distances are too short with respect to the Cepheid distances. An unweighted mean of the differences shown in Column (4) of Table 1 gives the size of the offset as:

$$(m\text{-}M)_{Cepheid} - (m\text{-}M)_{TF} = 0.50 \pm 0.14 \text{ mag.}$$

This difference is significant at the 3.6σ level. Excluding IC4182, NGC4321 and NGC4571 on the grounds that they have low inclinations and therefore less well determined TF distances, the remaining eight galaxies give

$$(m\text{-}M)_{Cepheid} - (m\text{-}M)_{TF} = 0.42 \pm 0.14 \text{ mag.}$$

Again this result is significant at the 3σ level and the inclusion or exclusion of the lower inclination galaxies makes no difference to the result. We adopt the average between the above two offset as :

$$(m\text{-}M)_{Cepheid} - (m\text{-}M)_{TF} = 0.46 \pm 0.14 \text{ mag} \qquad (1)$$

as our best estimate of the overall offset.

Figure 1b shows the plot of SNIa distance versus TF distance for the twelve galaxies in Table 2. Although the errors on the SNIa distances are frequently larger than for the Cepheid galaxies in Fig. 1, the same systematic trend can be seen in this Figure with the TF distances again being too short with respect to the SNIa distances. An unweighted mean of the differences shown in Column (6) of Table 2 gives the size of the offset as:

$$(m\text{-}M)_{SN\ Ia} - (m\text{-}M)_{TF} = 0.43 \pm 0.16 \text{ mag.}$$

This result is therefore significant at the 2.7σ level. Removing the four galaxies containing the heavily absorbed SN 1937D, SN 1957A, SN 1976B, SN1989B produces the offset:

$$(m\text{-}M)_{SN\ Ia} - (m\text{-}M)_{TF} = 0.49 \pm 0.21 \text{ mag}$$

corresponding to a bigger offset but at a slightly reduced significance of 2.3σ. We shall adopt the average value

$$(m\text{-}M)_{SN\ Ia} - (m\text{-}M)_{TF} = 0.46 \pm 0.19 \text{ mag} \qquad (2)$$

as characterising the offset in this case. Clearly both the HST Cepheid and the SNIa supernovae are consistently and independently suggesting that the previous TF distance moduli are too low. Weighting the results in equations (1) and (2) in inverse proportion to the square of the errors produces the final result for the TF offset from the HST Cepheid and the SNIa samples as

$$(m\text{-}M)_o - (m\text{-}M)_{TF} = 0.46\pm0.11 \text{ mag} \quad (3)$$

where the offset is now significant at the 4.2σ level.

4. Discussion.

Fig. 2 shows the combined Cepheid/SNIa-TF distance comparison which now also includes the six previous primary calibrators of Pierce & Tully (1992). Including the six previous primary calibrators in the HST Cepheid sample slightly reduces the Cepheid-TF distance modulus offset from the value in equation (1) to 0.36±0.11mag and the combined Cepheid/SNIa distance offset from the value in equation (3) to 0.39±0.095mag. But if the simplest interpretation of Fig. 2 is that there is some form of scale error with distance in the Tully-Fisher relation then the best estimate of the average offset for *distant* TF galaxies, such as those used in H_o estimation, is given by equation (3). The suggestion is that the previous TF calibration gave distances which were too short by 24±6% for galaxies at the distance of Virgo. Thus, for example, the TF Virgo and Ursa Major distances of 15.6±1.5 and 15.5±1.2 Mpc quoted by Pierce and Tully (1988) have to be increased to 19.3±1.9Mpc and 19.2±1.5Mpc. The value of H_o=84±10kms^{-1}Mpc^{-1} from Pierce (1991) from consideration of the Tully-Fisher distance to the above clusters therefore reduces to H_o=68± 8kms^{-1}Mpc^{-1}.

We now discuss the possible reasons for the error in the previous Tully-Fisher calibration. The first possibility we consider is that the field environment of the six local calibrators causes systematic differences with TF galaxies found in cluster environments such as Virgo, Ursa Major and Fornax. However, Table 1 shows that several cluster galaxies such as NGC1365 (Fornax) and NGC4321 (Virgo) have smaller residuals in the Cepheid-TF comparison than many other galaxies. Of course, there is always the possibility that these two galaxies are actually foreground to their respective clusters but we conclude that at present there is no immediate, positive evidence for a simple environmental effect.

Next we consider whether the Tully-Fisher distance residuals may correlate with galaxy colour. Pierce & Tully (1992) reported that five of the six local calibrators lay at the extreme blue edge of the distance independent colour-linewidth plane formed by Virgo and Ursa Major Tully-Fisher galaxies. They argued that this might just be indicative of extra star-formation affecting the B band in the local calibrators and so I band Tully-Fisher distances might not be affected. However, another possibility is that galaxy colour might be a second parameter for the Tully-Fisher relation and the new availability of highly accurate Cepheid distances to TF galaxies offers a further opportunity to investigate this issue. In Fig. 3, we therefore compare the position of the Cepheid galaxies in the corrected B-I colour-linewidth plane with the position of the primary and secondary local TF calibrators, and other TF galaxies (see also Pierce & Tully, 1992, Fig. 2b). A line has been drawn to mark the upper envelope of the local TF calibrators at the blue edge of this relation. Below the line, close to the local calibrators, lie four Cepheid-TF galaxies (crosses), NGC1365, NGC3351, NGC3621 and NGC 4321 and from Table 1 (Col. 4) and from Fig. 1a, it can be seen that these are the galaxies for which the Cepheid-TF residuals are smallest. However, Table 2 (Col. 6) and Fig. 1b also show that this correlation of residuals with colour is not repeated in the colour-linewidth plane for the supernova galaxies since NGC2841, NGC3389, NGC5055 and NGC6384 (open circles) lie close

to the calibrators at the blue edge of the distribution but the first three show large Cepheid-TF residuals. Thus the question of whether galaxy colour represents a second parameter for the TF relation remains open at this point.

The other possibilities are that either the linewidths or the Cepheid distances of the six local calibrators are systematically wrong. However, the 21cm measurements of the linewidths are generally supported by optical rotation curve measurements. Also, although the Cepheid distances to the local calibrators was initially based on older photographic data, checks using modern CCD photometry have, in general, confirmed these results (e.g. Metcalfe & Shanks, 1991). We conclude that the reason for the problem with the previous, local calibration of the Tully-Fisher distance scale is presently unknown, although it may be that a combination of several of the above effects is operating.

While this paper was in preparation, a preprint was circulated by Giovanelli et al (1996) who use eight of the galaxies in Table 1 together with the six previous primary calibrators to produce a new calibration of the TF relation. Although basing their results on a smaller sample size, with no use made of the SNIa galaxies, and although preferring to rederive TF parameters independently rather than use those previously published by Pierce (1994), these authors arrive at the same conclusion as this paper for their revised TF estimate of H_o, finding H_o=69±5kms^{-1}Mpc^{-1} (Giovanelli et al, 1996).

We finally note that our estimate of H_o=68± 8kms^{-1}Mpc^{-1} from the Tully-Fisher spiral distance scale is now in excellent agreement with the value of H_o=69± 8kms^{-1}Mpc^{-1} derived from the early-type galaxy distance scale calibrated via the HST Cepheid distance to the Leo group (Tanvir et al, 1995). Thus the HST has now given evidence for a ≈25% upwards revision of the traditional "short" distance scale using both early and late-type galaxies. However, the fact that such a mature distance

indicator as Tully-Fisher has proven to have a problem at this level warns against over-confidence that we have therefore reached the final value of H_o. As one example, it should be noted that the calibration of the Cepheid P-L relation depends on distances determined via main sequence fitting to Galactic star clusters at several kiloparsecs distance in the Galactic plane. These distances may therefore be suspect both because of the wide main sequence found for local stars by Hipparcos parallax measurements (M.J. Penston & F. van Leeuwen, priv. comm.) and because of the large, ($A_V \approx 2$ mag), foreground absorption typically found in front of these clusters. Together with the continuing cosmological timescale problem which even the revised Tully-Fisher estimate of $H_o = 68 \pm 8 \mathrm{kms}^{-1} \mathrm{Mpc}^{-1}$ implies for the theoretically preferred $\Omega_o = 1$ model, there is clearly strong motivation for future work at every rung of the distance scale step ladder.

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Figures.

Fig. 1(a). The comparison of Tully-Fisher and HST Cepheid true distance moduli for galaxies where both have been measured. The Tully-Fisher moduli are systematically shorter than the Cepheid moduli by 0.46±0.14 mag. The four filled squares indicate the galaxies which lie near the local calibrators at the blue edge of the colour-linewidth diagram in Fig. 3 (below the line) whereas the filled circles represent galaxies with redder colours; it can be seen that the bluer galaxies have the smallest Cepheid-TF distance modulus offsets.

Fig. 1(b). The comparison of Tully-Fisher and SNIa true distance moduli for galaxes where both have been measured. The Tully-Fisher moduli are systematically shorter than the Cepheid moduli by 0.46±0.19 mag. The four open squares indicate the galaxies which lie near the local calibrators at the blue edge of the colour-linewidth diagram in Fig. 3 (below the line) whereas the open circles represent galaxies with redder colours; the bluer galaxies show less tendency to have smaller distance modulus residuals in the comparison here than in Fig. 1a.

Fig. 2. The overall comparison of Cepheid-TF (filled circles) and SNIa-TF (open circles) true distance moduli, now also showing the position of the six original local calibrators from Pierce & Tully (1992) as the open squares. The Tully-Fisher moduli are systematically shorter than the HST Cepheid/SNIa moduli by 0.46±0.11 mag.

Fig. 3. The corrected (B-I) colour-linewidth plot for Ursa Major spirals (Pierce & Tully, 1988), the original primary and secondary Tully-Fisher calibrators (Pierce & Tully, 1992), the spirals with HST Cepheid distances (Table 1) and the spirals with SNIa distances (Table 2). The blue edge of this plot below the straight line is the

locus of the local primary and secondary calibrators. The four HST Cepheid galaxies with the smallest residuals in the Cepheid-TF comparison (NGC1365, NGC3351, NGC3621 and NGC 4321(see Table 1, Column 4, Fig. 1a) also lie in this region near the primary and secondary calibrators. However, less correlation between SNIa-TF residual and position in this plane is seen since NGC2841 (SN1957A), NGC3389 (SN1967C), NGC5055 (SN1971I) and NGC6384 (SN1971L) all lie below or on the line but the first three show large SNIa-TF distance residuals (see Table 2, Column 6, Fig. 1b).